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On the Correlation between Microstructure, Texture and Magnetic Induction in Non-oriented Electrical Steels

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***Abstract*—Although it is well known that the magnetic induction of electrical steels at a given applied field critically depends on the microstructure and on the present crystallographic texture, there is still no quantitative model to describe this relation in the whole range of inductions. In this paper, the existing different models for the dependence of B_8, B_{25} and B_{50} on the texture intensities will be evaluated in detail. Finally, a more general model is proposed for the dependence of the magnetic induction at a given applied field as a function of the mean grain size, a texture related parameter and the Si content of the material.**

***Index Terms*—Crystallographic texture, Grain size, Magnetic induction, Silicon steel**

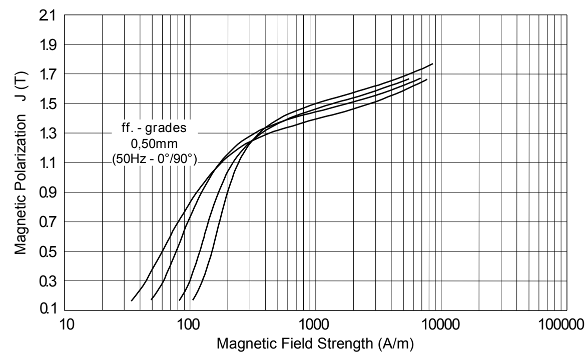

Figure 1. Magnetization behavior of different fully finished non-oriented electrical steels [7].

I. Introduction

It is well known that the microstructural features and the intensities of the different texture components as well as the magnitude of the magnetostriction determine the magnetization behavior in soft magnetic materials. There is still no quantitative model, which describes these relations in the complete range of magnetic inductions There are only a limited amount of papers, which establish a correlation between the measured texture intensities and the resulting values of B_{25}, i.e. the magnetic induction B at a field of 2500A/m [1]–[4]. Wiesinger [5] calculated values of B_{25} for mixtures of various magnetically relevant texture components and fibres with different intensities based on the data obtained for the value of B_{25} for single crystals of different crystallographic orientations. Following a method used by Lawton and Stewart, de Campos [6] calculated the magnetic induction B_{25} and B_{50} considering only the saturation magnetization M_S and the first order magnetocrystalline anisotropy constant K_1. Generally speaking, it can be said that the crystallographic texture is important because the anisotropic behavior of the magnetostriction and the magnetization behavior of the bcc lattice of iron is different along the different crystallographic directions. It is well known that $<100>$ directions are much more easily magnetized than $<110>$ or $<111>$ directions. In polycrystalline materials, the existing texture determines the remanent magnetic induction and the domain rotation processes at high values of the applied external magnetic field. Apart from the crystallographic texture, different other microstructural features have a strong influence on the magnetic properties, i.e. the grain size, inclusions, internal stresses and surface defects. These microstructural features determine the domain wall pinning, i.e. the coercive force of the material, and the domain wall motion, which are responsible for the magnetizing behavior at low and medium values of the applied external magnetic field and for the hysteresis losses. Microstructure and texture are strongly influenced by the processing conditions during hot and cold rolling as well as during the subsequent annealing treatment. Variations of the annealing conditions, which result in a decrease of the specific magnetic losses, give mostly lower values of the permeability in the medium and high field region. Fig. 1 shows the typical magnetizing behavior of different commercial grades of non-oriented electrical steels. While one obtains quite different behavior at low applied magnetic fields the magnetizing behavior at medium and high fields becomes more or less similar.

In this paper, the existing different models for the dependence of B as a function of the value of the applied field on the relevant structural parameters and on the intrinsic material parameters will be critically evaluated. Finally, a more general model is proposed for the dependence of the magnetic induction at a given applied field as a function of the mean grain size, a texture-related parameter and the Si content of the material.

II. Experimental Procedure

The materials chosen for this work were commercially produced non-oriented electrical steels with Si content up to 3.3 wt%. The grain size D was determined by optical microscopy using the linear interception method. The crystallographic texture was measured using Electron BackScatter Diffraction (EBSD). The magnetic measurements were done for Epstein strips using a commercial Brockhaus® magnetic measurement unit. For discussing the effects of the crystallographic texture of the material, an appropriate parameter has to be defined. Therefore, we will calculate the so-called A parameter from the obtained EBSD data as was previously demonstrated in [8]. Kestens and Van Houtte suggested [9] that the "quality of the magnetic texture" can be characterized by defining the minimum angle $A_\alpha(g)$ between one of the <100> directions of easy magnetization of the crystals in the polycrystalline material and the direction of the macroscopic magnetization vector M in the material. The externally applied magnetic field, which is represented by this magnetization vector M, makes an angle α with respect to the rolling direction (RD) of the sheet. The experimentally determined orientation distribution function (ODF) is reflected in the function f(g). The orientation g is defined by its Euler angles. The volume fraction of orientations in an infinitesimal environment of g is given by f(g)dg. Finally, a texture parameter A_α is defined in (1).

$$A_\alpha = \int A(g)f(g)dg \tag{1}$$

Where A_α is the texture parameter in the case that the magnetic field vector M is applied in a direction making an angle α with the rolling direction. The average A-parameter of a material is given in (2).

$$A = \int Ad\alpha \tag{2}$$

III. Modelling the B vs. H Behavior

In scientific literature, different approaches to establish a correlation between the value of induction B at a given applied field and the microstructure and texture of the material can be found [3], [4], [9]–[11]. In [3], [4], [11] the following formula is proposed, which correlates B_{25} with different C ODF coefficients (C_4^{11}, C_4^{12} and C_4^{13}):

$$B_{25}(C) = p_0+p_1*C_4^{11}+p_2*C_4^{12}*cos(2*\alpha)+p_3*C_4^{13}*cos(4*\alpha) \tag{3}$$

The different constants p_0, p_1, p_2 and p_3 are material parameters and α gives the angle between the direction of the applied field and the rolling direction of the electrical steel strips. This formula was applied on our data. The calculated values B_{cal} at the magnetic field $H = 2500A/m$ for the used Fe-Si alloys, with quite different Si content, as a function of the C coefficients at α = 0°, are not in good agreement with the experimentally obtained values B_{25} parallel to the rolling direction, see Fig. 2. It seems that the material constants p_i differ for the studied alloys when the Si content changes. It should also be mentioned that the samples showed some texture gradients throughout thickness, which might have a detrimental effect on the determination of the C coefficients of the ODF. If an additional term $p_4 * Si_{eq}$ is added, where Si_{eq} is defined as $(Si+2*Al)$ in wt%, the agreement between B_{cal} and B_{meas} becomes better, as is shown in Fig. 2.

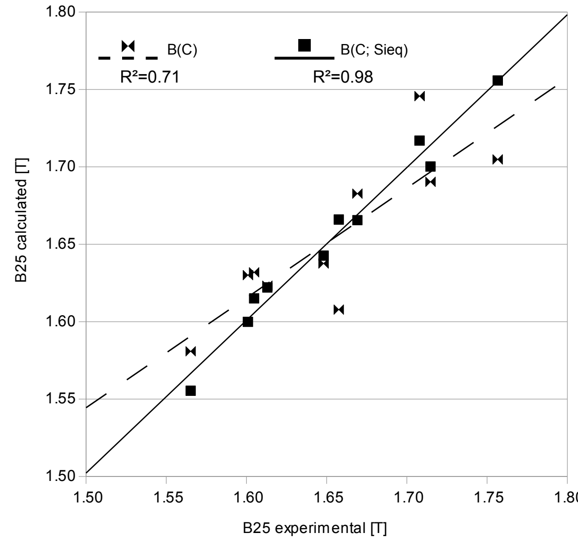

Figure 2. Correlation of B_{25}experimental and B_{25}calculated using (3), with and without the Si_{eq} term.

Instead of the C coefficients we will use in the following the parameter A to describe the texture of the material. Fig. 3 gives as an illustration the evolution of the A_α value as a function of α for some specific ideal crystallographic orientations and texture fibres. Fig. 4 gives the calculated values of B_{25} as a function of the A parameter for different combinations of texture fibres and components as defined by Wiesinger [5]. The letters in Fig. 4 refer to the nomenclature that Wiesinger used in his work to define this different texture combinations. In Fig. 4, the B_{25} values are those calculated by Wiesinger [5] and the A parameter was calculated by using the A_α (α = 0°) values of Fig. 3. The highest values of B_{25} at α = 0° will be obtained for the lowest values of A. The calculated values of B_{25} in [5] are, however, "maximum values", which may be reached in the ideal case that the magnetizing behavior is only influenced by the crystallographic texture.

The question might, however, arise whether or not the A parameter is the ideal parameter to represent the crystallographic texture and whether or not the magnetic anisotropy energy E_a would be a better alternative. In the ideal case, a linear dependence between the A parameter and the magnetic anisotropy energy E_a would be expected. Fig 5 shows E_a as a function of the A parameter for the Fe-Si steels with variable Si content investigated in this work. $E_a$and A were calculated for α = 0°. The perfectly linear relationship between both parameters demonstrates that both parameters can be used and motivates the decision why it is a valuable choice to continue the calculations using the A parameter to describe the influence of the crystallographic texture.

Apart from the influence of the texture, the effect of the silicon content was investigated as well. For the commercial Fe-Si steels studied, the relation B_{25} was plotted as a function of the Si_{eq} content as shown in Fig. 6. Although the observed relation was not linear, a general tendency was found of a decrease in B_{25} for increasing values of Si_{eq}. This might

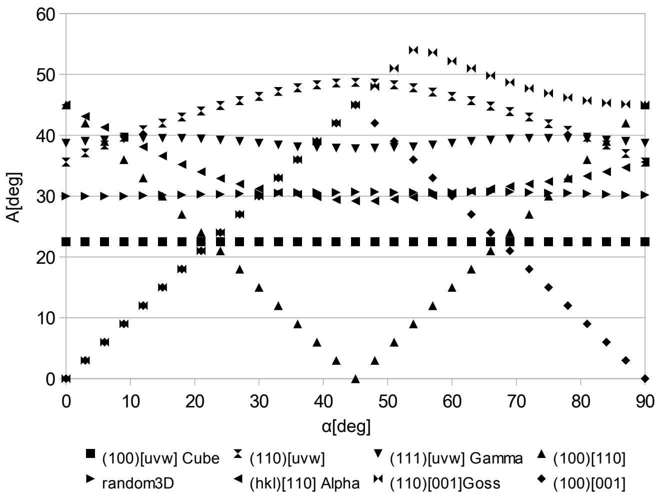

Figure 3. Evolution of the A parameter as a function of the most common texture components and fibres.

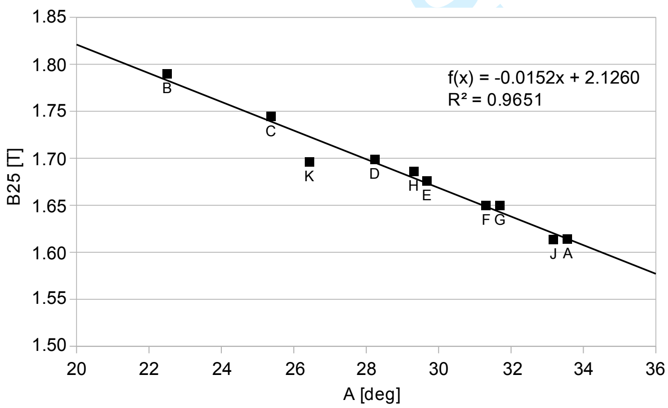

Figure 4. B_{25} values calculated in [5] for various mixtures of magnetic relevant textures vs. the value of A for these texture intensities

be related to the fact that silicon causes a decrease of the saturation induction and might consequently also affect the value of B_{25} , that means the values of the magnetic induction in the high field region, in a similar way. The effect of the texture described by the parameter A and the Si_{eq} content was combined by using the following equation:

$$B_H(A, Si_{eq}) = p_0 + p_1 * A + p_2 * Si_{eq} \tag{4}$$

As can be seen from Table I and is illustrated in Fig. 7, apart from the low field region, a reasonable agreement between the calculated and measured values of B_{25} at $\alpha = 0°$ is obtained. In the low field region, i.e. $H < 300A/m$, as can be seen from Fig. 1, there is a quite different behavior for the regarded commercial Fe-Si steels.

Subsequently, since one could expect that the microstructural features, especially the mean grain size, affect the magnetizing behavior. One observes a decrease of B as function of the grain size D at different values of the applied field. The non-linear dependence seems to indicate a dependence such

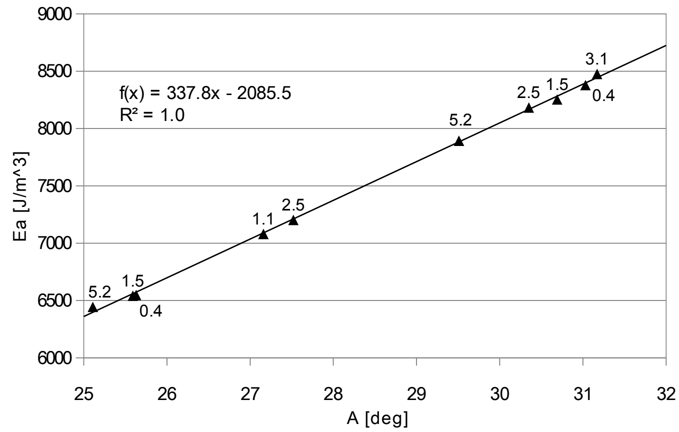

Figure 5. Calculated magnetic anisotropy energy E_a as a function of the A for $\alpha = 0°$. Values obtained from the ODF for the investigated Fe-Si materials with different Si content.

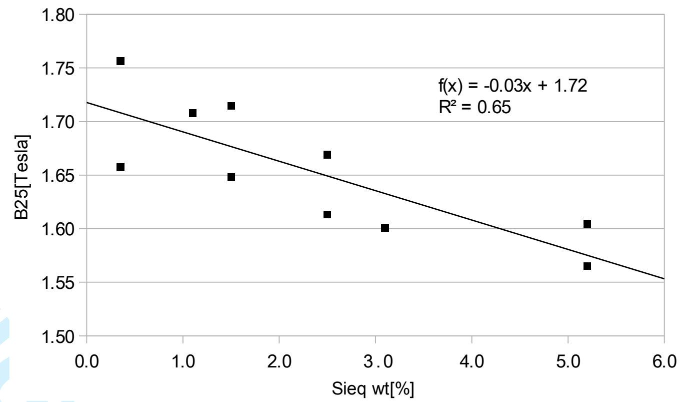

Figure 6. Influence of Si_{eq} on B_{25}.

as B proportional to $1/D$, as may be correlated with the fact that the critical field for domain movement is proportional to $1/D$. An equation including the effect of the grain size may be proposed:

$$B_H(D, A, Si_{eq}) = p_0 + p_1 * A + \frac{p_2}{D} + p_3 * Si_{eq} \tag{5}$$

As can be seen from Table II, one obtains even a slightly better agreement between the calculated and measured values of B at different applied fields parallel to the rolling direction for the Fe-Si steels studied. The R^2 values range from 0.95 to

Table I
VALUES OF THE PARAMETER p_0, p_1 AND p_2, SEE (4) FOR B AT DIFFERENT VALUES OF THE APPLIED FIELD (E.G. B_2 = B AT 200 A/M AND SO ON).

	p_0	$p_1 \rightarrow A$	$p_2 \rightarrow Si_{eq}$	R^2
B_2	1.98	-0.023	-0.01	0.61
B_5	1.92	-0.014	-0.03	0.94
B_8	1.98	-0.013	-0.03	0.97
B_{15}	2.04	-0.013	-0.03	0.96
B_{25}	2.12	-0.014	-0.03	0.98
B_{40}	2.16	-0.014	-0.03	0.97
B_{50}	2.20	-0.014	-0.03	0.98

Table II
VALUES OF THE PARAMETER p_0, p_1, p_2 AND p_3, SEE (5) FOR B AT DIFFERENT VALUES OF THE APPLIED FIELD (E.G. B_2 = B AT 200 A/M AND SO ON).

	p_0	$p_1 \rightarrow A$	$p_2 \rightarrow D$	$p_3 \rightarrow Si_{eq}$	R^2
B_2	1.92	-0.015	-2.70	-0.04	0.79
B_5	1.91	-0.012	-0.56	-0.03	0.95
B_8	1.96	-0.012	-0.52	-0.03	0.98
B_{15}	2.03	-0.012	-0.24	-0.03	0.96
B_{25}	2.11	-0.013	-0.26	-0.03	0.98
B_{40}	2.16	-0.013	-0.25	-0.03	0.97
B_{50}	2.19	-0.013	-0.27	-0.03	0.99

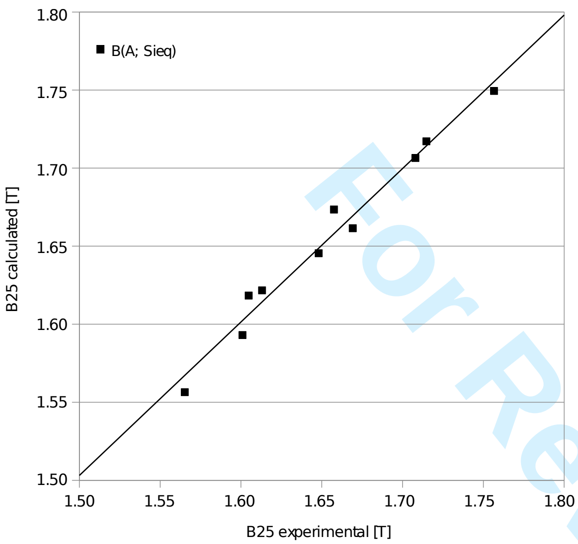

Figure 7. B_{calc} using (4) vs. B_{meas}.

0.99, except in the low field region ($H < 300A/m$) were the fit fails again.

As can also be seen from Table II, the effect of the grain size becomes increasingly important for lower values of the maximum applied field, whereas the parameters p_1 and p_3, which reflect the influence of A and the Si content, are almost constant. The equations (4) and (5) were also used for analyzing the values of B measured at applied fields perpendicular to the rolling direction using A(α = 90°). The general trend observed is similar as that for B measured parallel to the rolling direction. Also in this case, the effect of the grain size becomes more and more important at decreasing values of the maximum applied magnetic field.

IV. CONCLUSIONS

In the present work, existing and alternative models are discussed to correlate the dependence of the magnetic induction at a given applied field with the mean grain size, the texture-related A parameter and the Si content of the material. It was found that the field dependence of the magnetic induction B for commercial electrical steels with variable composition and processing parameters may be well described for $H > 300A/m$ by taking into account the influence of the crystallographic textures, the grain size and the chemical composition. The magnetization behavior at very high values of the applied field H is mainly determined by the magnetic anisotropy. At decreasing values of the applied magnetic field the effect of the grain size is found to increase. The validity of the regarded equations seems to be restricted to the region above the maximum value of the permeability $\mu_{max} = B/H$. In the low field region, where μ is smaller than μ_{max} the effect of the microstructural features: grain size, precipitations, and internal stresses on the resulting maximum values of B appears to be more important and has to be analyzed further. The effect of internal stresses is connected with the value of the magnetostriction, which can be related with the Si content. The results indicate that by an independent variation of the grain size and magnetic texture the magnetization behavior at medium and high fields may be varied in a broader way. Therefore, a deeper understanding of the evolution of the microstructure and texture during the process of fabrication of electrical steels is important.

ACKNOWLEDGMENT

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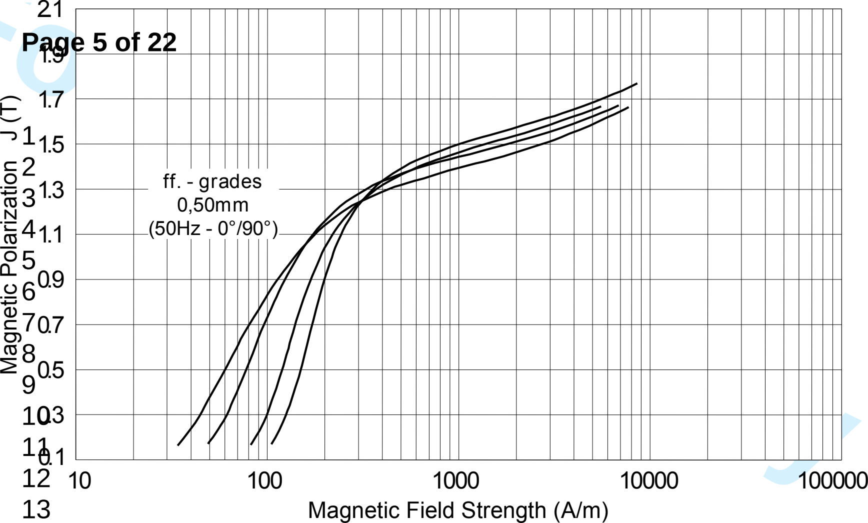
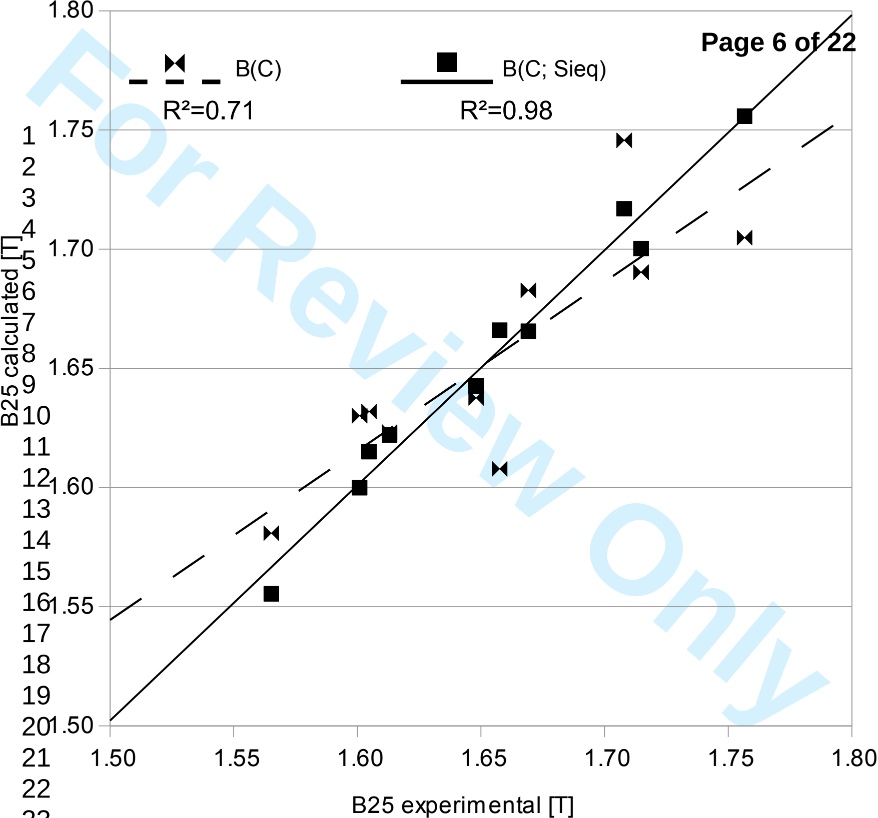
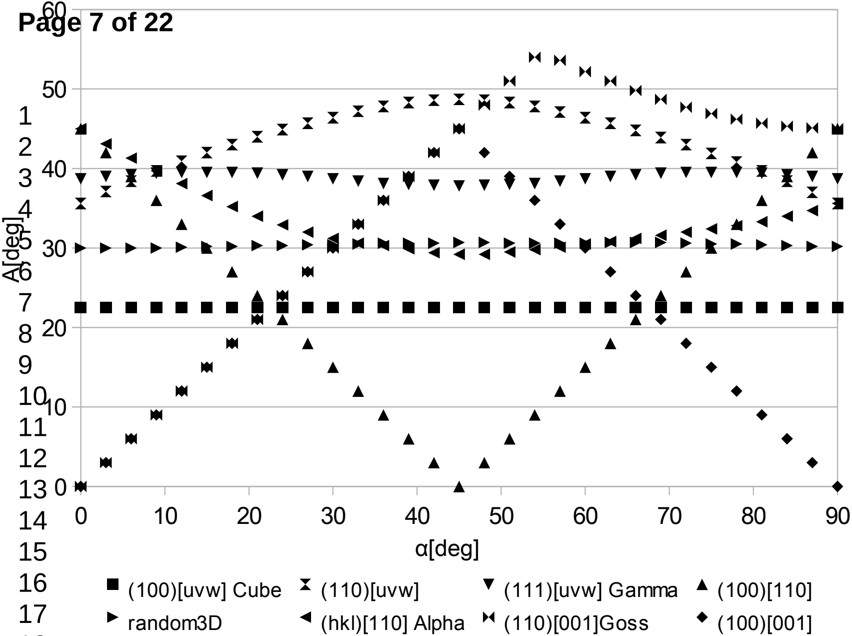
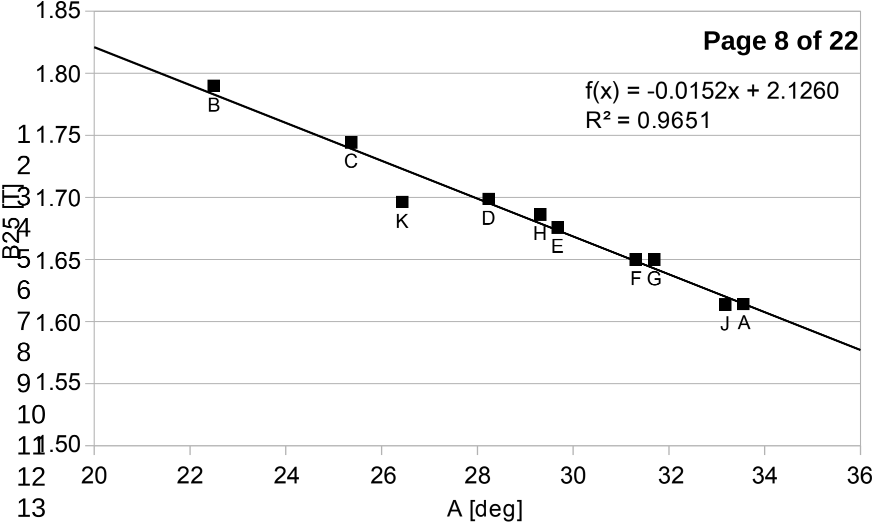

ff. - grades
0,50mm
(50Hz - 0°/90°)
Magnetic Polarization J (T)
1.9
1.7
1.5
1.3
1.1
0.9
0.7
0.5
0.3
0.1
10
100
1000
10000
100000
Magnetic Field Strength (A/m)


B(C)
B(C; Sieq)
R²=0.71
R²=0.98
B25 calculated [T]
B25 experimental [T]
1.50
1.55
1.60
1.65
1.70
1.75
1.80


A[deg]
α[deg]
0
10
20
30
40
50
60
70
80
90
(100)[uvw] Cube
(110)[uvw]
(111)[uvw] Gamma
(100)[110]
random3D
(hkl)[110] Alpha
(110)[001]Goss
(100)[001]


f(x) = -0.0152x + 2.1260
R² = 0.9651
B25 [T]
A [deg]
1.85
1.80
1.75
1.70
1.65
1.60
1.55
1.50
20
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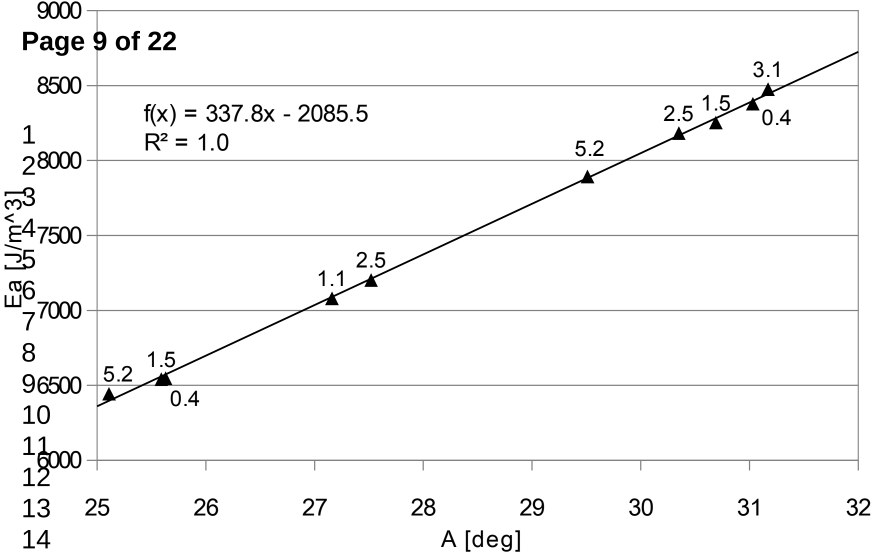
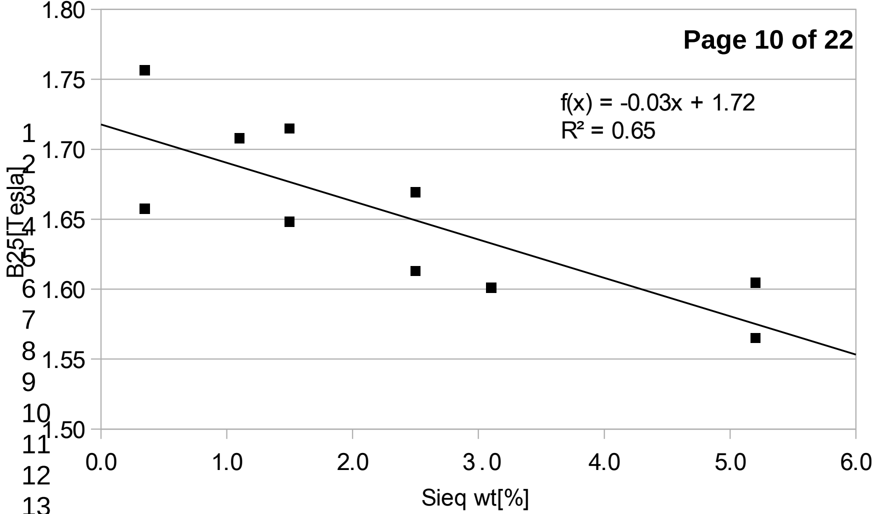
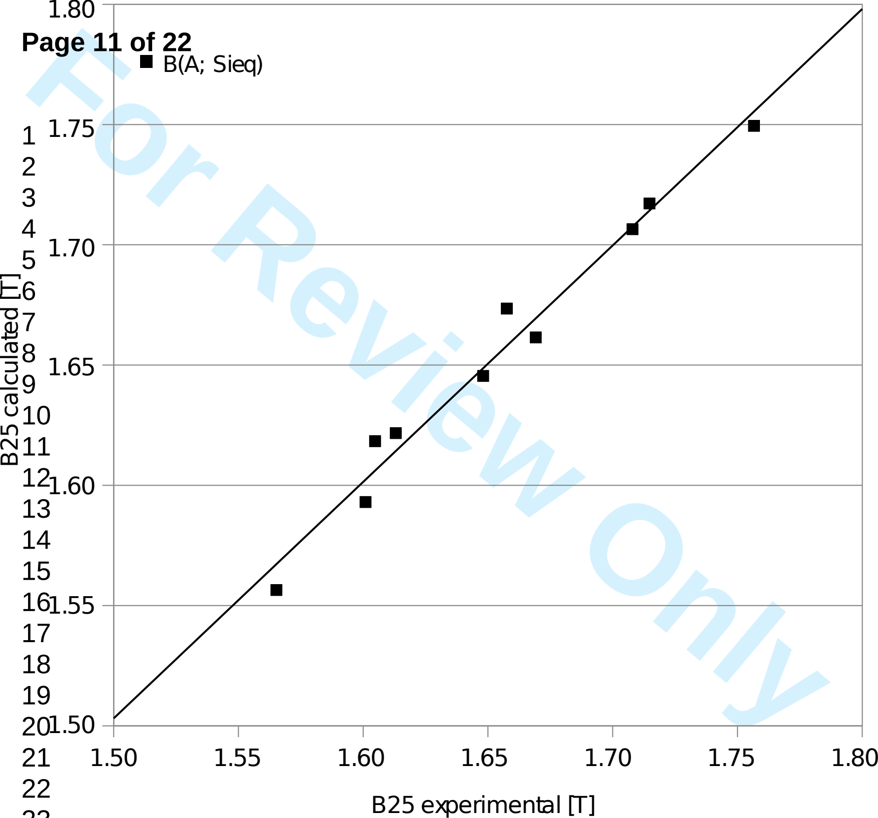
E
F
G
J
A


f(x) = 337.8x - 2085.5
R² = 1.0
Ea [J/m^3]
A [deg]
9000
8500
8000
7500
7000
6500
6000
25
26
27
28
29
30
31
32
5.2
1.5
0.4
1.1
2.5
5.2
2.5
1.5
0.4
3.1


f(x) = -0.03x + 1.72
R² = 0.65
B25[Tesla]
1.80
1.75
1.70
1.65
1.60
1.55
1.50
0.0
1.0
2.0
3.0
4.0
5.0
6.0
Sieq wt[%]


B(A; Sieq)
1.80
1.75
1.70
1.65
1.60
1.55
1.50
B25 calculated [T]
1.50
1.55
1.60
1.65
1.70
1.75
1.80
B25 experimental [T]

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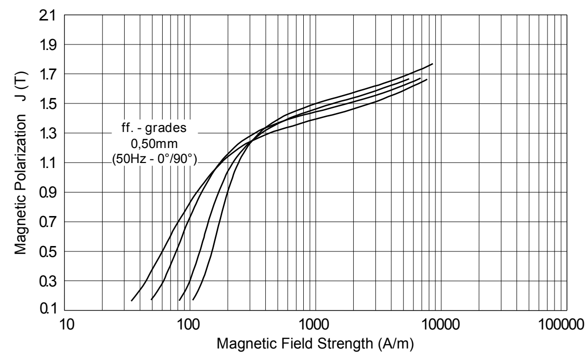

Figure 1. Magnetization behavior of different fully finished non-oriented electrical steels [8].

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III. Modelling the B vs. H Behavior

In scientific literature, different approaches to establish a correlation between the value of induction B at a given applied field and the microstructure and texture of the material can be found [3], [4], [10]–[12]. In [3], [4], [12] the following formula is proposed, which correlates B_{25} with different C ODF coefficients (C_4^{11}, C_4^{12} and C_4^{13}):

$$B_{25}(C) = p_0 + p_1 * C_4^{11} + p_2 * C_4^{12} * cos(2*\alpha) + p_3 * C_4^{13} * cos(4*\alpha) \tag{3}$$

The different constants p_0, p_1, p_2 and p_3 are material parameters and α gives the angle between the direction of the applied field and the rolling direction of the electrical steel strips. This formula was applied on our data. The calculated values B_{cal} at the magnetic field $H = 2500A/m$ for the used Fe-Si alloys, with quite different Si content, as a function of the C coefficients at α = 0°, are not in good agreement with the experimentally obtained values B_{25} parallel to the rolling direction, see Fig. 2. It seems that the material constants p_i differ for the studied alloys when the Si content changes.

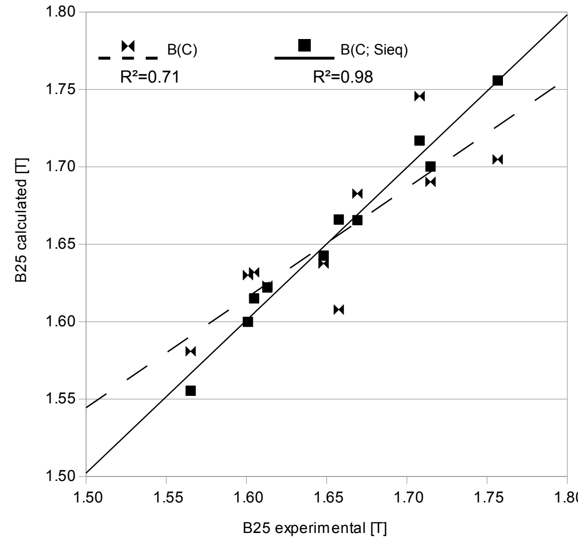

Figure 2. Correlation of B_{25}experimental and B_{25}calculated using (3), with and without the Si_{eq} term.

It should also be mentioned that the samples showed some texture gradients throughout thickness, which might have a detrimental effect on the determination of the C coefficients of the ODF. If an additional term $p_4 * Si_{eq}$ is added, where Si_{eq} is defined as $(Si+2*Al)$ in wt%, the agreement between B_{cal} and B_{meas} becomes better, as is shown in Fig. 2.

Instead of the C coefficients we will use in the following the parameter A to describe the texture of the material. Fig. 3 gives as an illustration the evolution of the A_α value as a function of α for some specific ideal crystallographic orientations and texture fibres. Fig. 4 gives the calculated values of B_{25} as a function of the A parameter for different combinations of texture fibres and components as defined by Wiesinger [5]. The letters in Fig. 4 refer to the nomenclature that Wiesinger used in his work to define this different texture combinations. In Fig. 4, the B_{25} values are those calculated by Wiesinger [5] and the A parameter was calculated by using the A_α (α = 0°) values of Fig. 3. The highest values of B_{25} at α = 0° will be obtained for the lowest values of A. The calculated values of B_{25} in [5] are, however, "maximum values", which may be reached in the ideal case that the magnetizing behavior is only influenced by the crystallographic texture.

The question might, however, arise whether or not the A parameter is the ideal parameter to represent the crystallographic texture and whether or not the magnetic anisotropy energy E_a would be a better alternative. In the ideal case, a linear dependence between the A parameter and the magnetic anisotropy energy E_a would be expected. Fig 5 shows E_a as a function of the A parameter for the Fe-Si steels with variable Si content investigated in this work. $E_a$and A were calculated for α = 0°. The perfectly linear relationship between both parameters demonstrates that both parameters can be used and motivates the decision why it is a valuable choice to continue the calculations using the A parameter to describe the influence of the crystallographic texture.

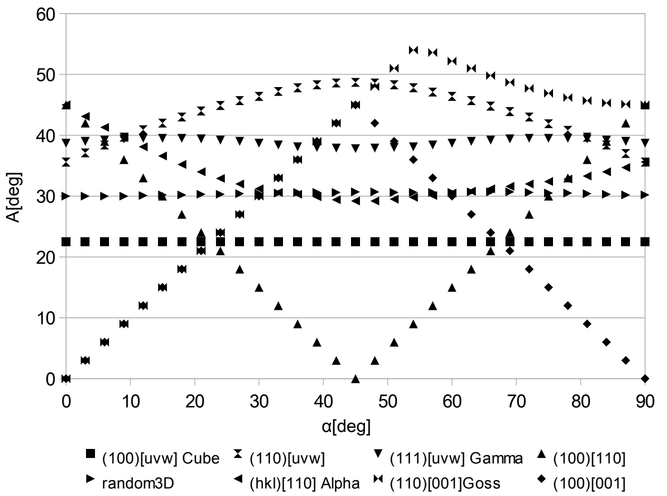

Figure 3. Evolution of the A parameter as a function of the most common texture components and fibres.

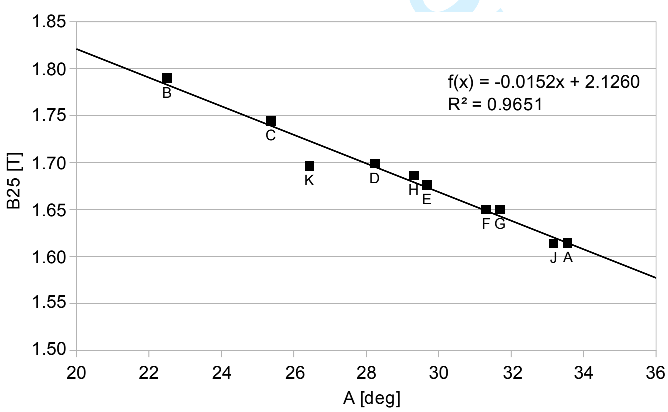

Figure 4. B_{25} values calculated in [5] for various mixtures of magnetic relevant textures vs. the value of A for these texture intensities

Apart from the influence of the texture, the effect of the silicon content was investigated as well. For the commercial Fe-Si steels studied, the relation B_{25} was plotted as a function of the Si_{eq} content as shown in Fig. 6. Although the observed relation was not linear, a general tendency was found of a decrease in B_{25} for increasing values of Si_{eq}. This might be related to the fact that silicon causes a decrease of the saturation induction and might consequently also affect the value of B_{25} , that means the values of the magnetic induction in the high field region, in a similar way. The effect of the texture described by the parameter A and the Si_{eq} content was combined by using the following equation:

$$B_H(A, Si_{eq}) = p_0 + p_1 * A + p_2 * Si_{eq} \quad (4)$$

As can be seen from Table I and is illustrated in Fig. 7, apart from the low field region, a reasonable agreement between the calculated and measured values of B_{25} at $\alpha = 0°$ is obtained. In the low field region, i.e. $H < 300A/m$, as can be seen from Fig. 1, there is a quite different behavior for the regarded commercial Fe-Si steels.

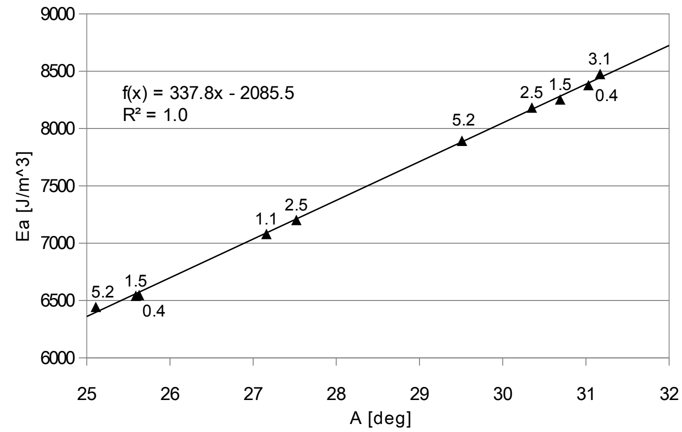

Figure 5. Calculated magnetic anisotropy energy E_a as a function of the A for $\alpha = 0°$. Values obtained from the ODF for the investigated Fe-Si materials with different Si content.

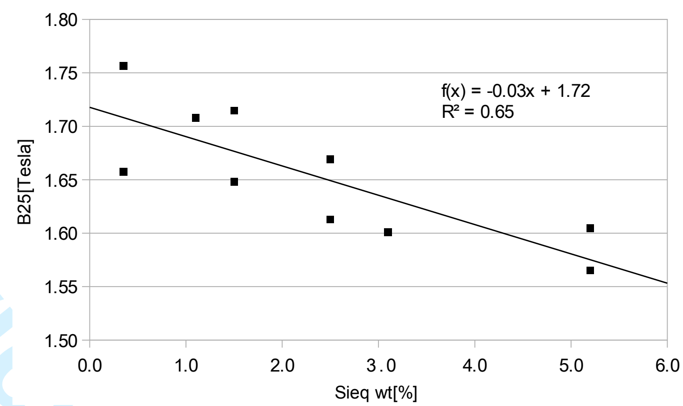

Figure 6. Influence of Si_{eq} on B_{25}.

Subsequently, since one could expect that the microstructural features, especially the mean grain size, affect the magnetizing behavior, one observes a decrease of B as function of the grain size D at different values of the applied field, as was also studied by [13]. The non-linear dependence seems to indicate a dependence such as B proportional to $1/D$, as may be correlated with the fact that the critical field for domain movement is proportional to $1/D$. An equation including the effect of the grain size may be proposed:

Table I
VALUES OF THE PARAMETER p_0, p_1 AND p_2, SEE (4) FOR B AT DIFFERENT VALUES OF THE APPLIED FIELD (E.G. B_2 = B AT 200 A/M AND SO ON).

	p_0	$p_1 \rightarrow A$	$p_2 \rightarrow Si_{eq}$	R^2
B_2	1.98	-0.023	-0.01	0.61
B_5	1.92	-0.014	-0.03	0.94
B_8	1.98	-0.013	-0.03	0.97
B_{15}	2.04	-0.013	-0.03	0.96
B_{25}	2.12	-0.014	-0.03	0.98
B_{40}	2.16	-0.014	-0.03	0.97
B_{50}	2.20	-0.014	-0.03	0.98

Table II
VALUES OF THE PARAMETER p_0, p_1, p_2 AND p_3, SEE (5) FOR B AT DIFFERENT VALUES OF THE APPLIED FIELD (E.G. B_2 = B AT 200 A/M AND SO ON).

	p_0	$p_1 \rightarrow A$	$p_2 \rightarrow D$	$p_3 \rightarrow Si_{eq}$	R^2
B_2	1.92	-0.015	-2.70	-0.04	0.79
B_5	1.91	-0.012	-0.56	-0.03	0.95
B_8	1.96	-0.012	-0.52	-0.03	0.98
B_{15}	2.03	-0.012	-0.24	-0.03	0.96
B_{25}	2.11	-0.013	-0.26	-0.03	0.98
B_{40}	2.16	-0.013	-0.25	-0.03	0.97
B_{50}	2.19	-0.013	-0.27	-0.03	0.99

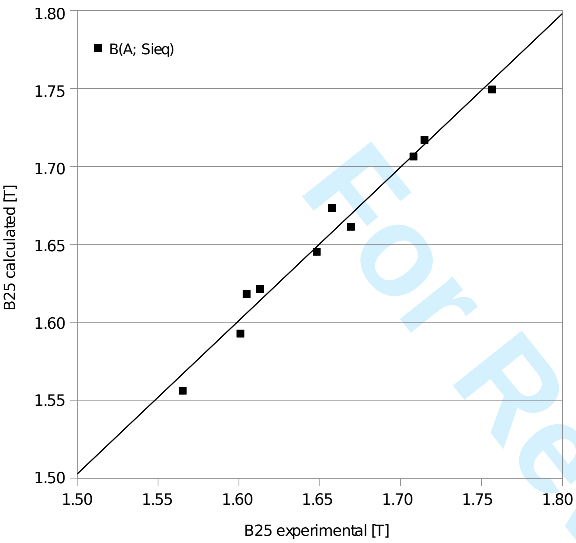

Figure 7. B_{calc} using (4) vs. B_{meas}.

$$B_H(D, A, Si_{eq}) = p_0 + p_1 * A + \frac{p_2}{D} + p_3 * Si_{eq} \qquad (5)$$

As can be seen from Table II, one obtains even a slightly better agreement between the calculated and measured values of B at different applied fields parallel to the rolling direction for the Fe-Si steels studied. The R^2 values range from 0.95 to 0.99, except in the low field region ($H < 300A/m$) were the fit fails again.

As can also be seen from Table II, the effect of the grain size becomes increasingly important for lower values of the maximum applied field, whereas the parameters p_1 and p_3, which reflect the influence of A and the Si content, are almost constant. The equations (4) and (5) were also used for analyzing the values of B measured at applied fields perpendicular to the rolling direction using A(α = 90°). The general trend observed is similar as that for B measured parallel to the rolling direction. Also in this case, the effect of the grain size becomes more and more important at decreasing values of the maximum applied magnetic field.

IV. CONCLUSIONS

In the present work, existing and alternative models are discussed to correlate the dependence of the magnetic induction at a given applied field with the mean grain size, the texture-related A parameter and the Si content of the material. It was found that the field dependence of the magnetic induction B for commercial electrical steels with variable composition and processing parameters may be well described for $H > 300A/m$ by taking into account the influence of the crystallographic textures, the grain size and the chemical composition. The magnetization behavior at very high values of the applied field H is mainly determined by the magnetic anisotropy. At decreasing values of the applied magnetic field the effect of the grain size is found to increase. The validity of the regarded equations seems to be restricted to the region above the maximum value of the permeability $\mu_{max} = B/H$. In the low field region, where μ is smaller than μ_{max} the effect of the microstructural features: grain size, precipitations, and internal stresses on the resulting maximum values of B appears to be more important and has to be analyzed further. The effect of internal stresses is connected with the value of the magnetostriction, which can be related with the Si content. The results indicate that by an independent variation of the grain size and magnetic texture the magnetization behavior at medium and high fields may be varied in a broader way. Therefore, a deeper understanding of the evolution of the microstructure and texture during the process of fabrication of electrical steels is important.

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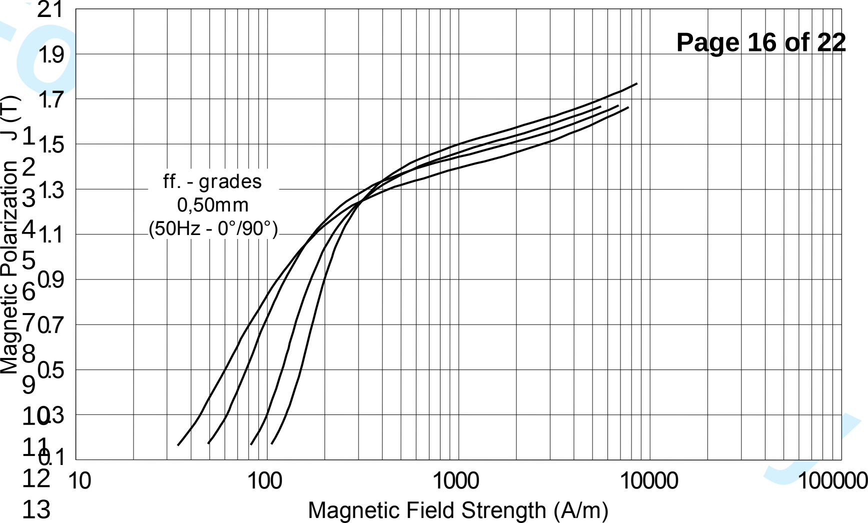
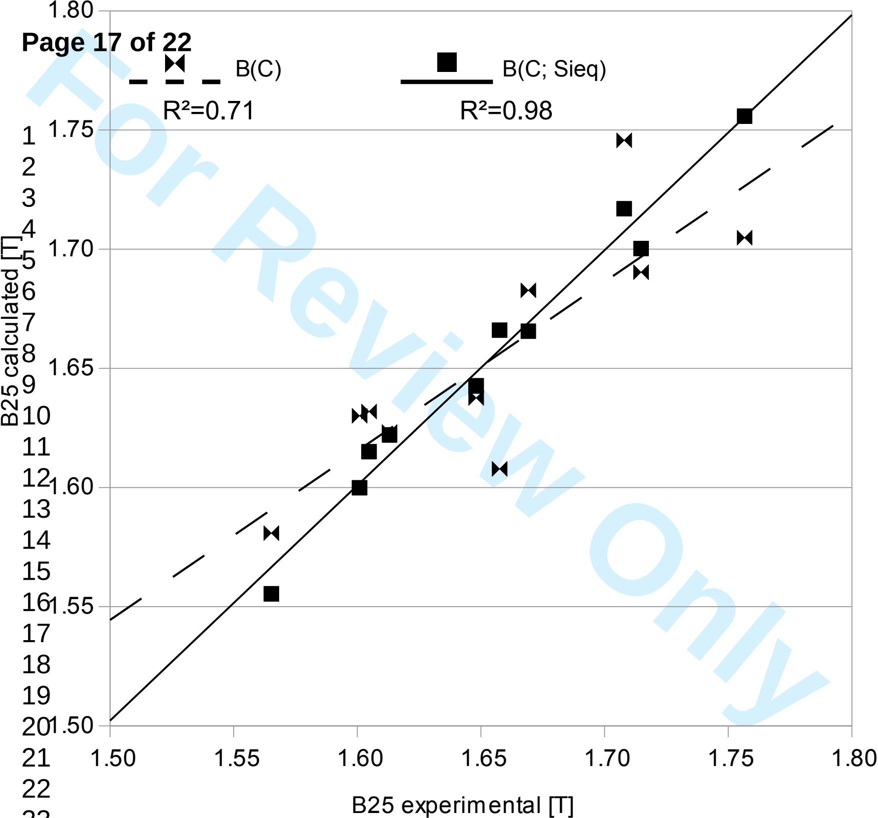
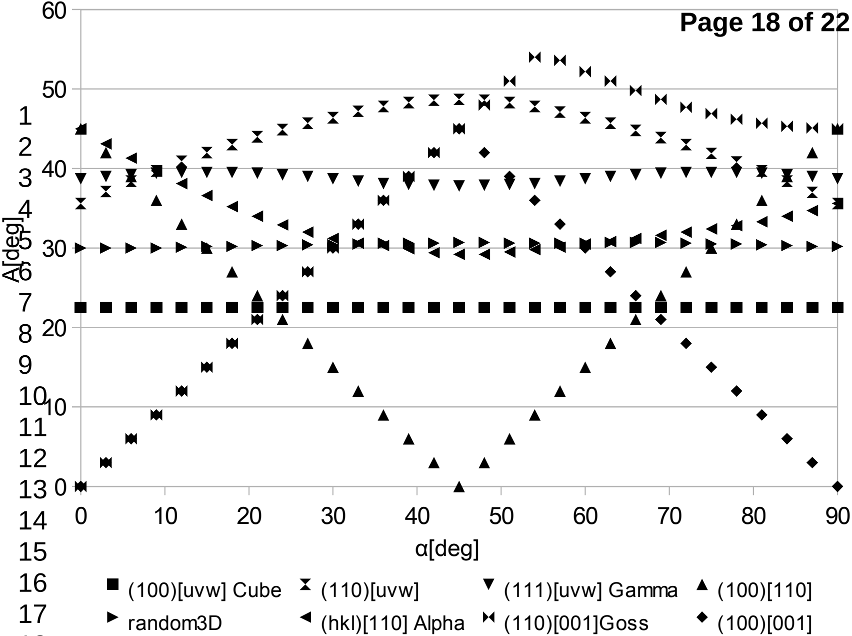
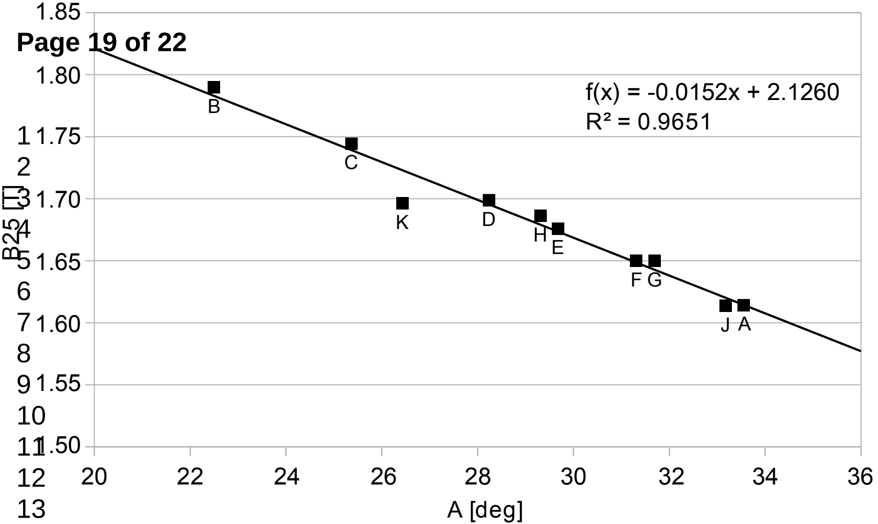
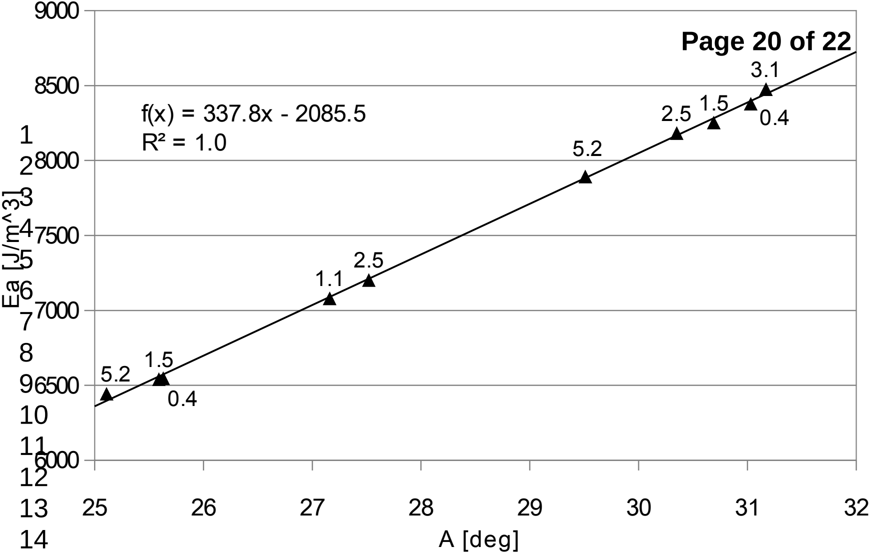
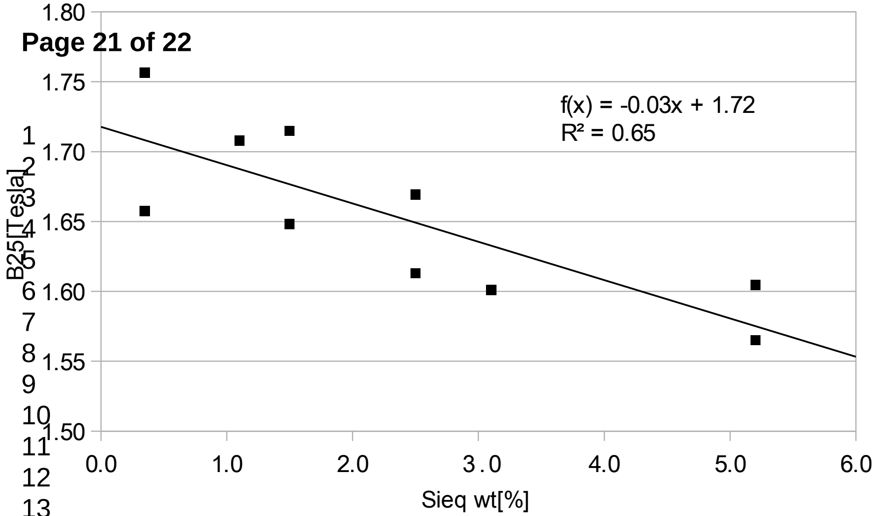

ff. - grades
0,50mm
(50Hz - 0°/90°)
Magnetic Polarization J (T)
2.1
1.9
1.7
1.5
1.3
1.1
0.9
0.7
0.5
0.3
0.1
10
100
1000
10000
100000
Magnetic Field Strength (A/m)

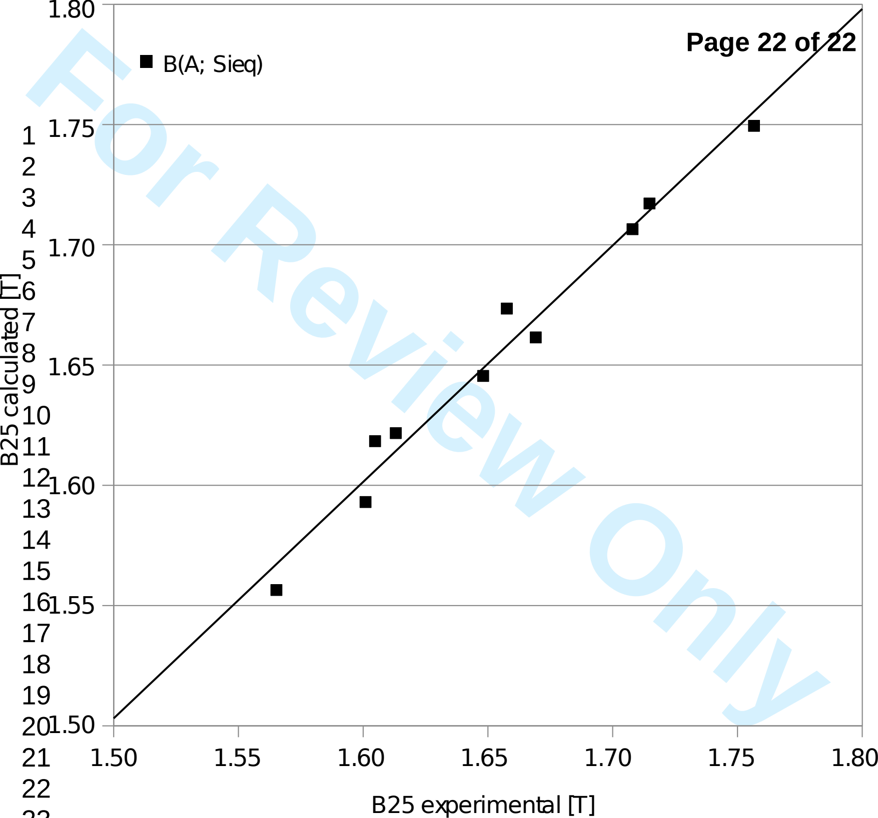

B(C)
R^2=0.71
B(C; Sieq)
R^2=0.98
B25 calculated [T]
B25 experimental [T]
1.50
1.55
1.60
1.65
1.70
1.75
1.80


A[deg]
α[deg]
0
10
20
30
40
50
60
70
80
90
(100)[uvw] Cube
(110)[uvw]
(111)[uvw] Gamma
(100)[110]
random3D
(hkl)[110] Alpha
(110)[001]Goss
(100)[001]


f(x) = -0.0152x + 2.1260
R² = 0.9651
B
C
K
D
H
E
F
G
J
A
B25 [T]
1.85
1.80
1.75
1.70
1.65
1.60
1.55
1.50
20
22
24
26
28
30
32
34
36
A [deg]


f(x) = 337.8x - 2085.5
R² = 1.0
Ea [J/m^3]
A [deg]
9000
8500
8000
7500
7000
6500
6000
25
26
27
28
29
30
31
32
5.2
1.5
0.4
1.1
2.5
5.2
2.5
1.5
3.1
0.4


f(x) = -0.03x + 1.72
R² = 0.65
B25[Tesla]
1.80
1.75
1.70
1.65
1.60
1.55
1.50
0.0
1.0
2.0
3.0
4.0
5.0
6.0
Sieq wt[%]


B(A; Sieq)
B25 calculated [T]
B25 experimental [T]
1.50
1.55
1.60
1.65
1.70
1.75
1.80